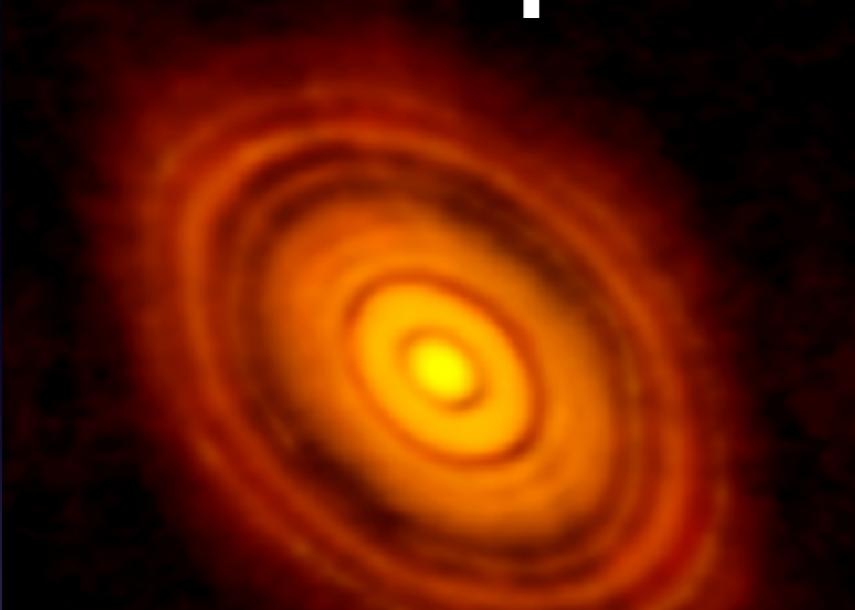
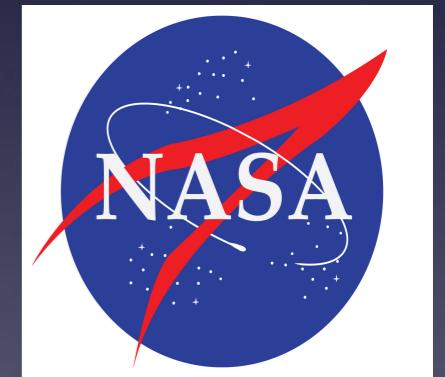
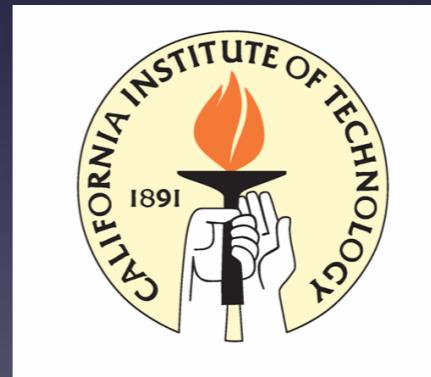
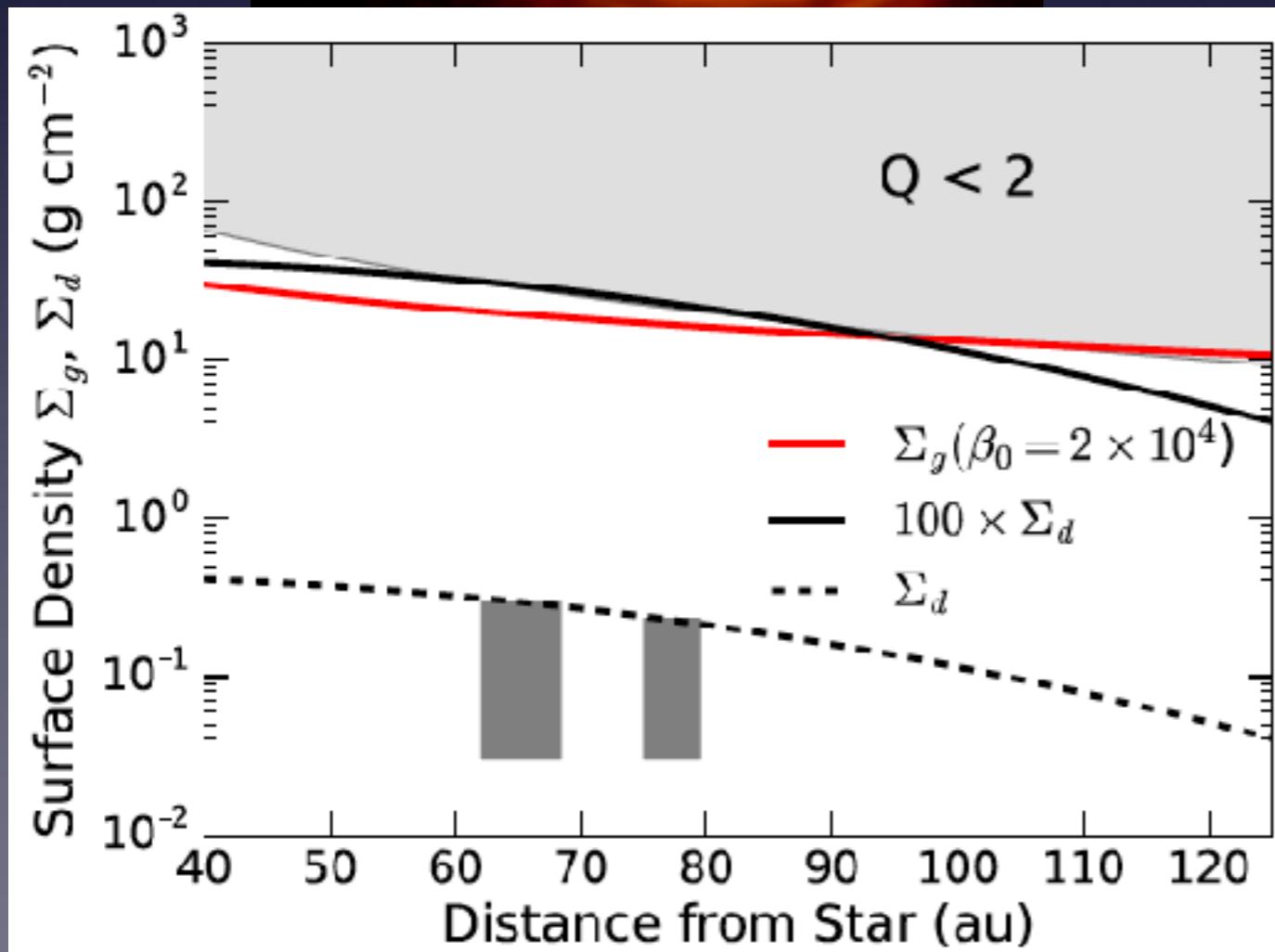


Magnetically Induced Disk Winds and Transport in the HL Tau Disk



Yasuhiro Hasegawa

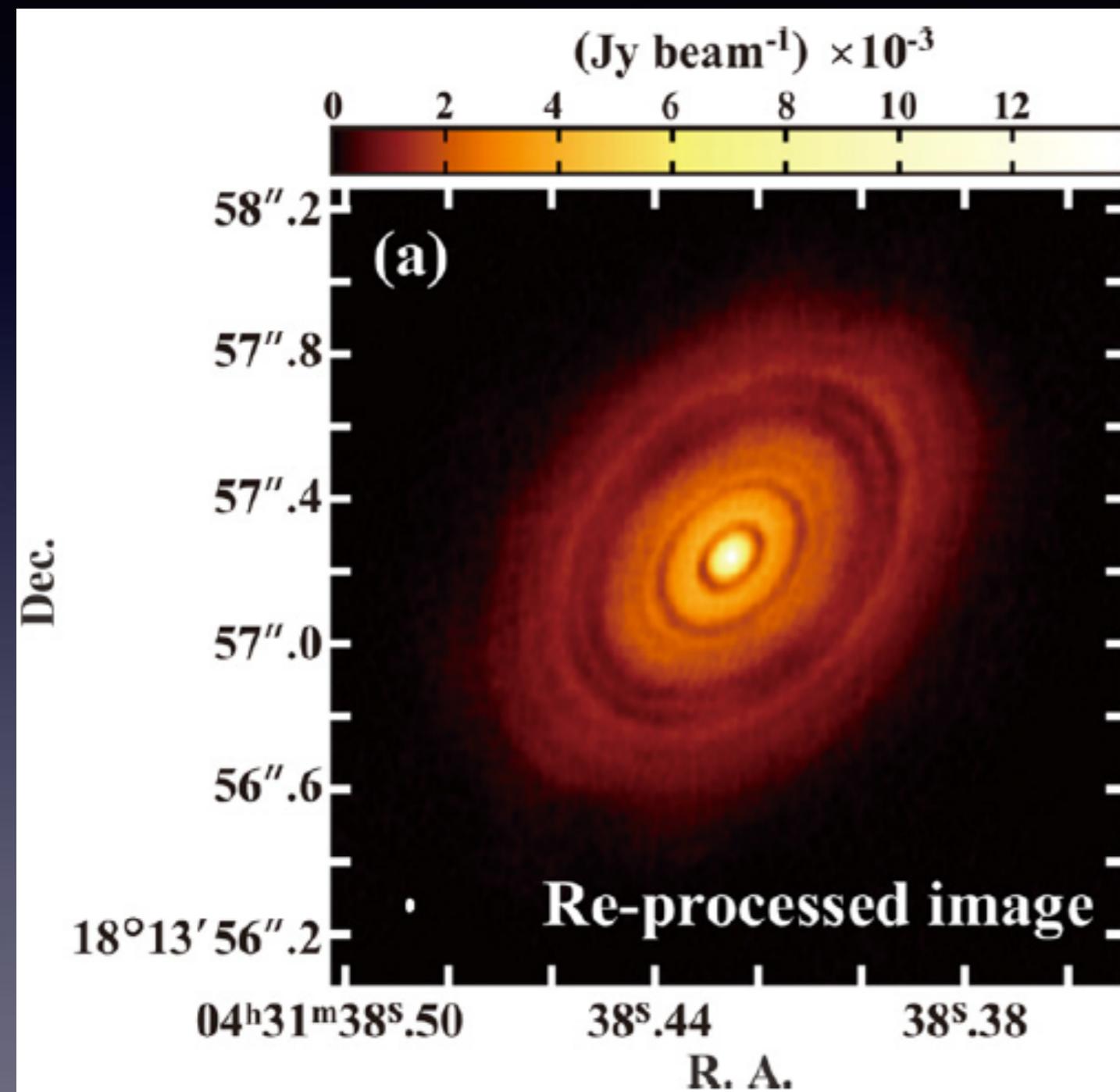
(Jet Propulsion Laboratory,
California Institute of Technology)



in collaboration with
Satoshi Okuzumi (TokyoTech)
Mario Flock (JPL/Caltech)
Neal Turner (JPL/Caltech)

Astonishing ALMA Images of HL Tau

ALMA Partnership et al 2015,
also see Akiyama YH et al 2016



HL Tau : a Class I/II YSO
: ~ 140 pc (< 1 Myrs)

Nearly concentric
multiple gaps in
the dust thermal emission

Potential signature of
planet formation

The origin of observed gaps is not identified yet!!

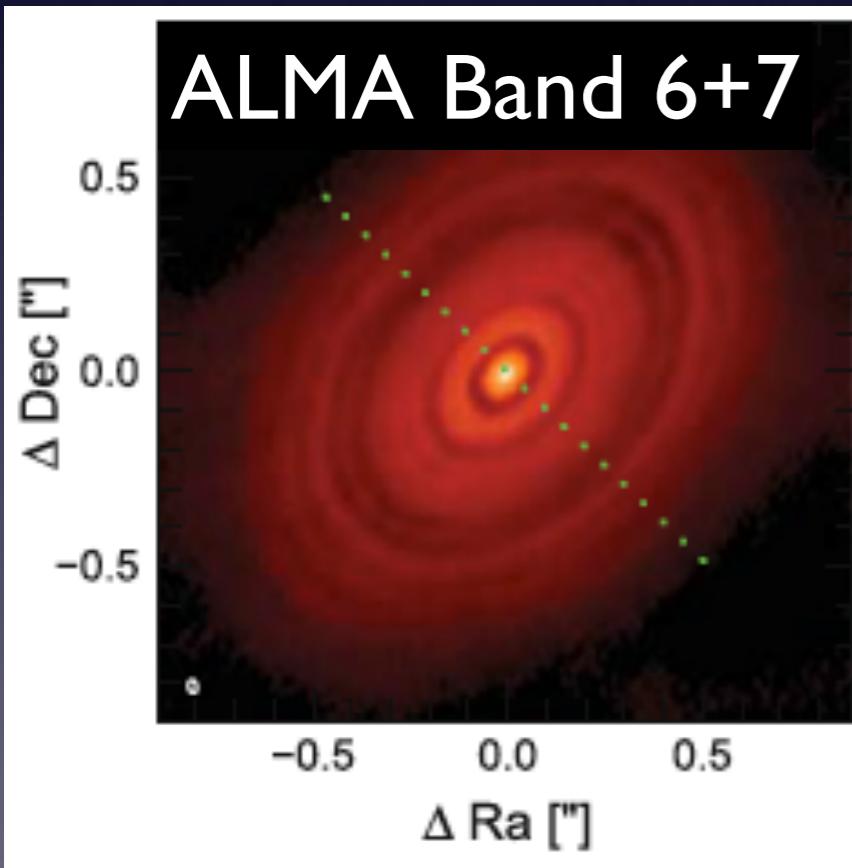
Global Properties of the HL Tau Disk

Disk accretion rate $\simeq 10^{-7} - 10^{-6} M_{\odot} \text{ yr}^{-1}$

Hayashi et al 1993, Beck et al 2010

Global diffusion coefficient : $\alpha_{\text{GL}} \simeq 10^{-2} - 10^{-1}$

=> can be explained by MRI and MHD turbulence



ALMA Partnership et al 2015
also see Akiyama et al 2016

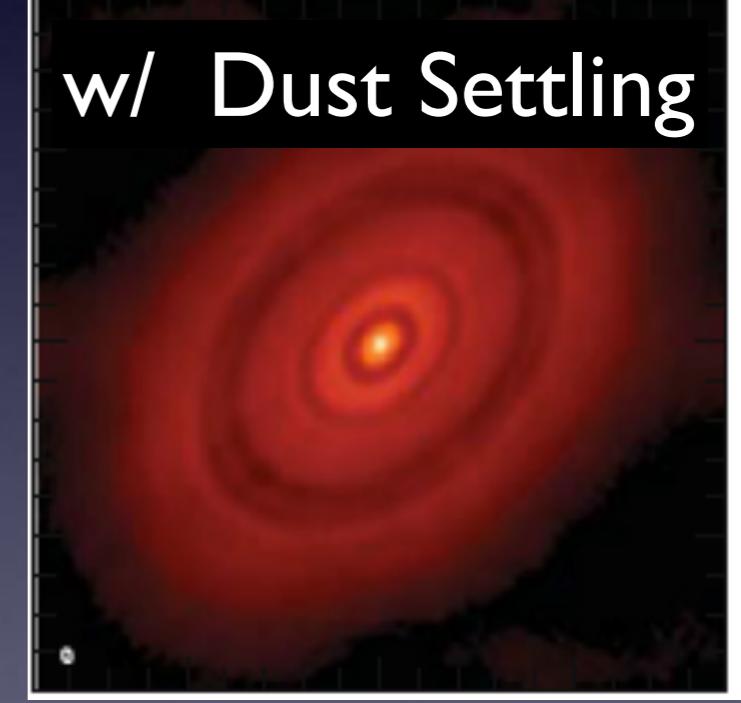
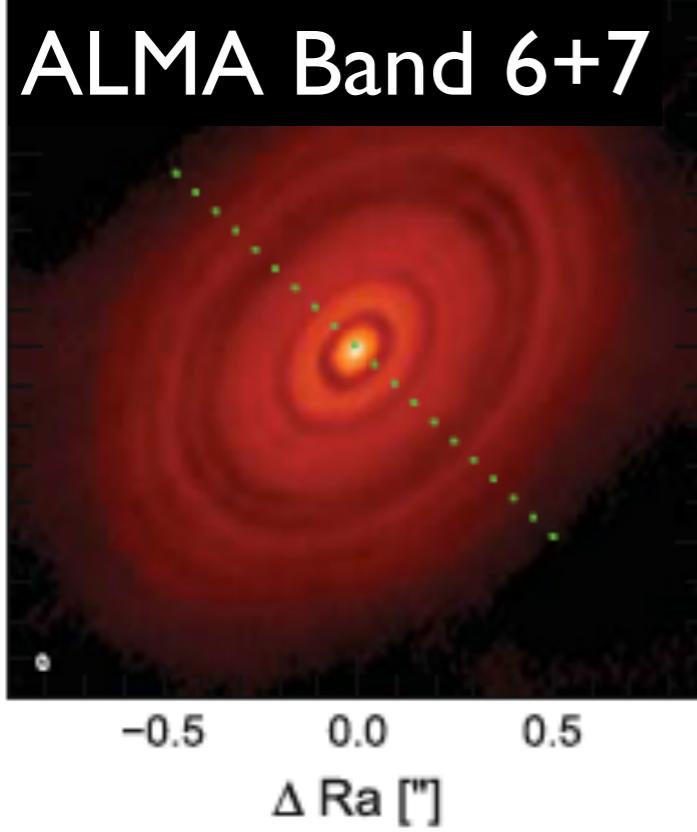
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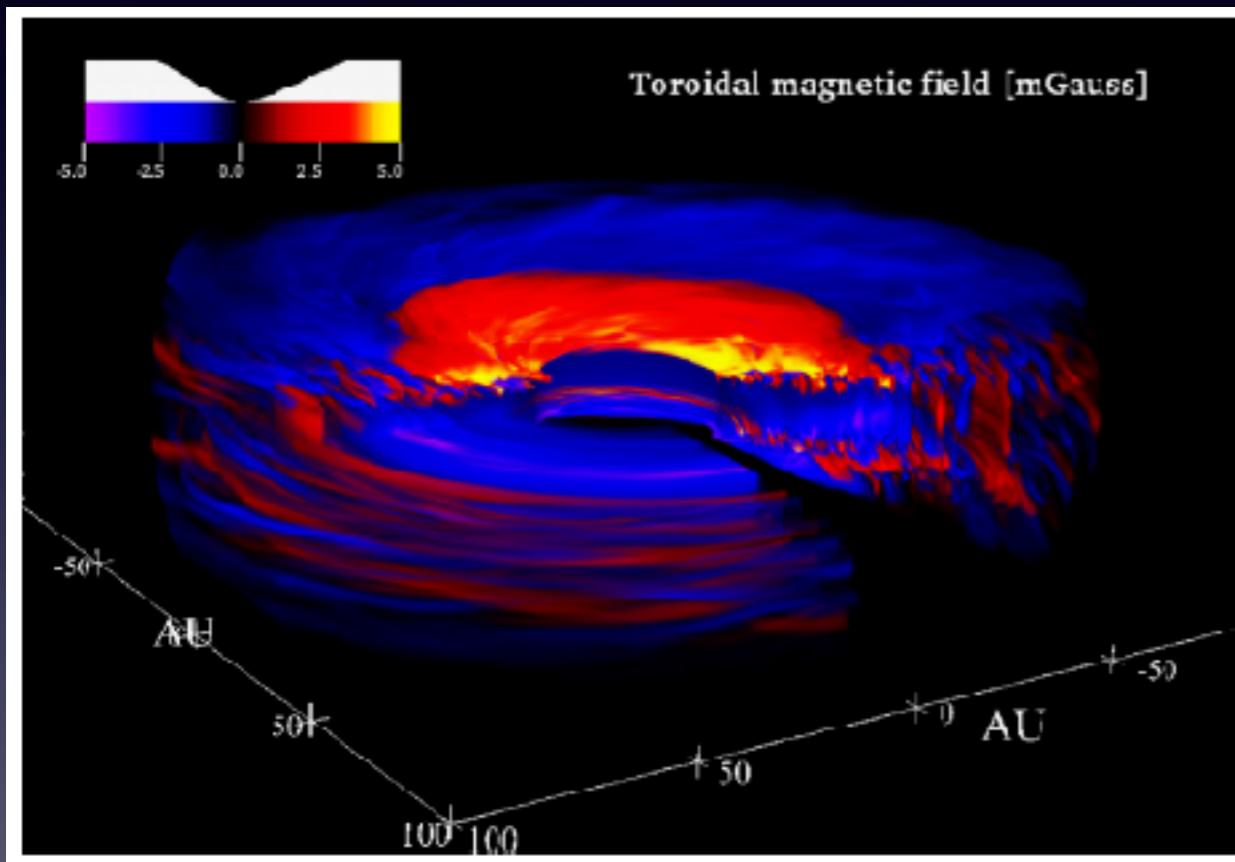
Pinte et al 2016

Vertical dust height: $\sim 1 \text{ au}$ at $r = 100 \text{ au}$
Local diffusion coefficient: $\alpha_{\text{LC}} \sim 10^{-4}$

Magnetically Driven Disk Accretion

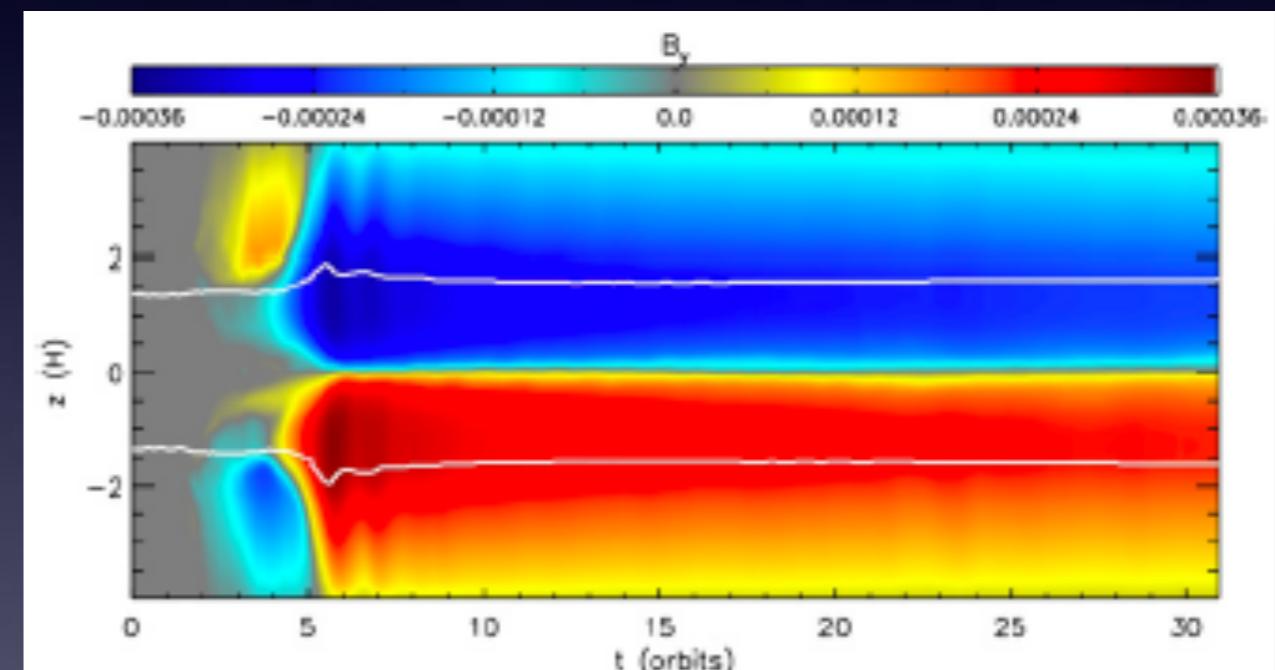
e.g., Armitage et al 2011, Bai & Stone 2013, Turner et al 2014, Suzuki et al 2016

Magnetized Turbulence



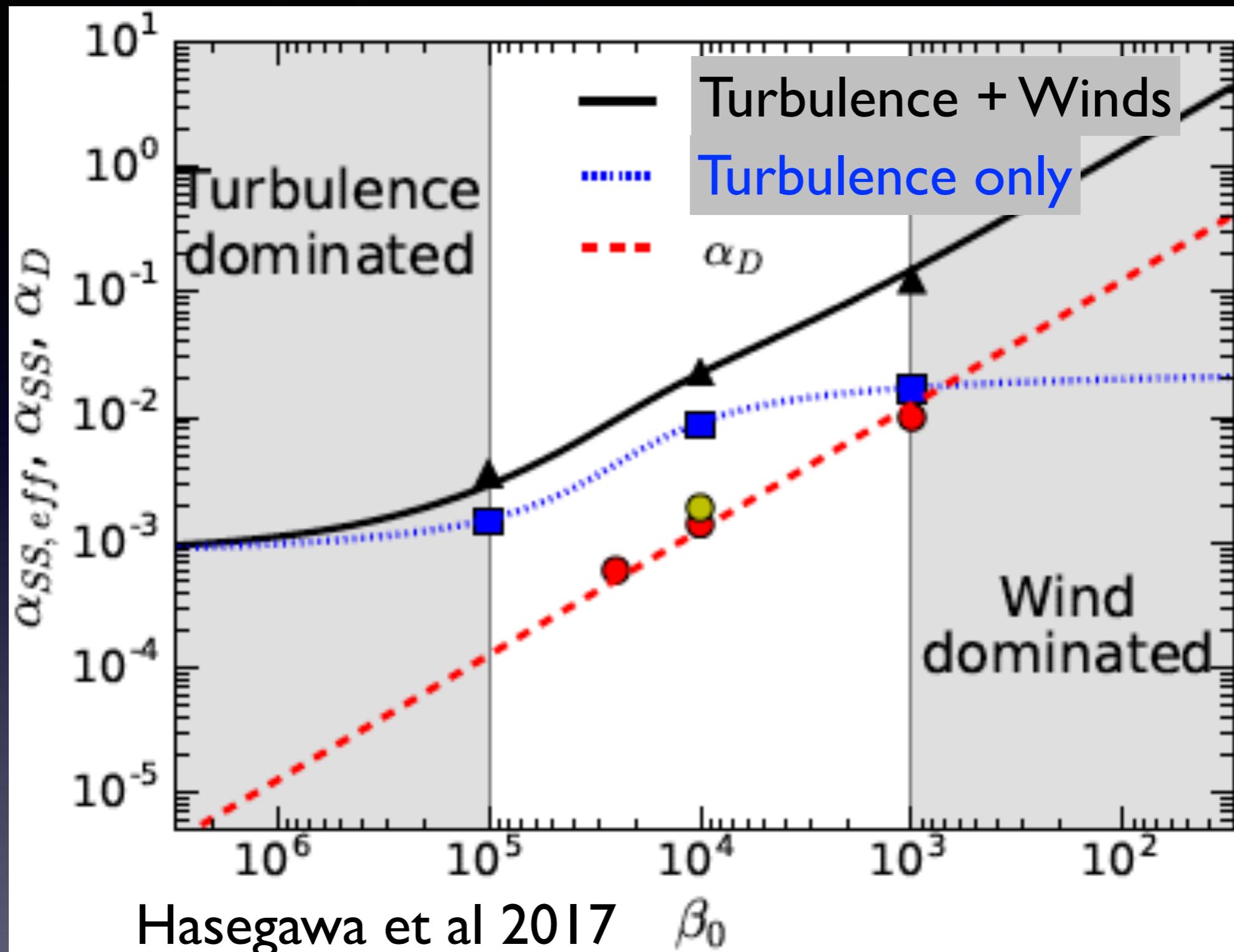
Flock et al 2015

Magnetically Induced Disk Winds



Simon et al 2013



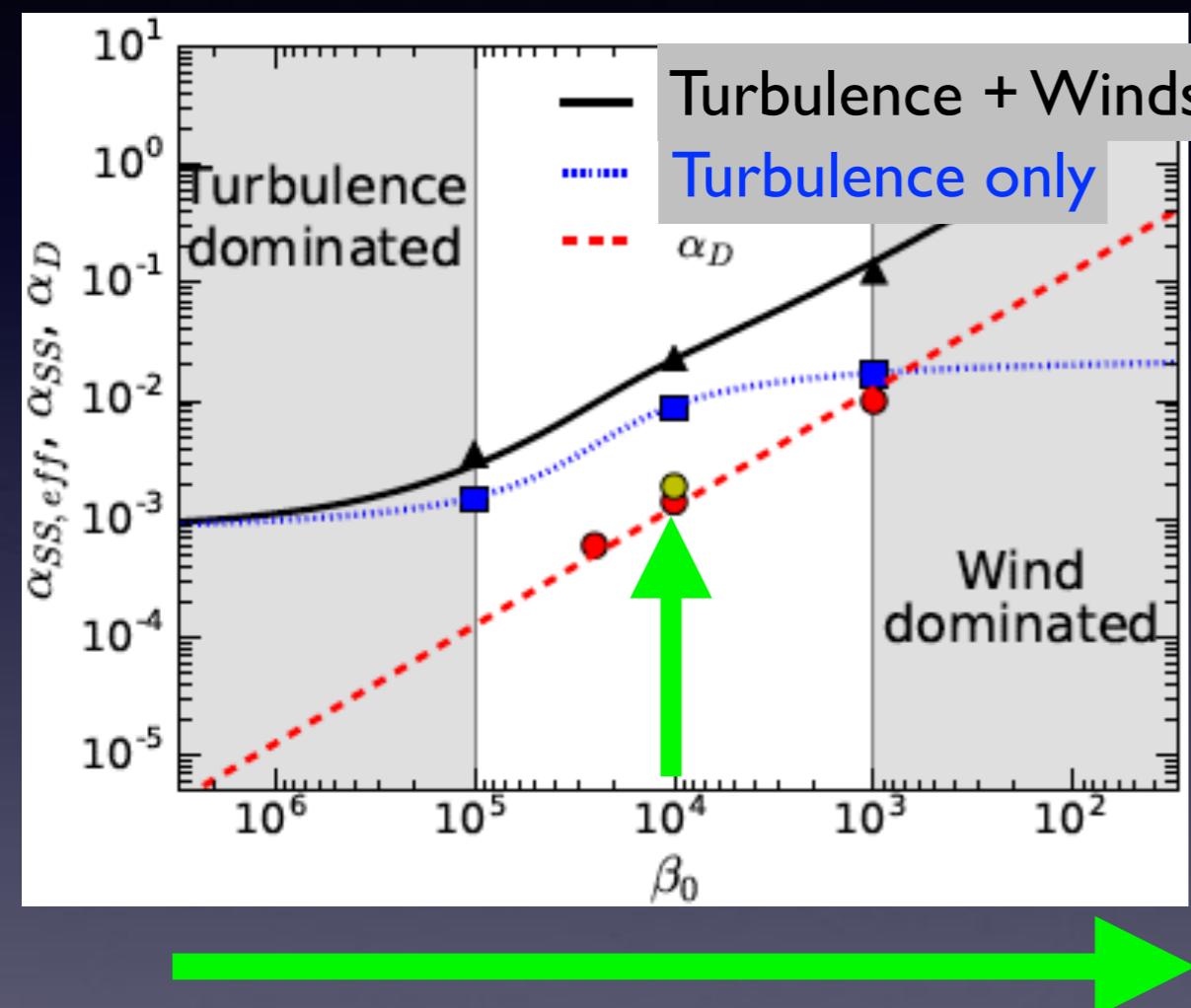


Simulation results from Simon et al 2013, Zhu et al 2015 are used

I. Gas surface density

Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$



2. Dust height

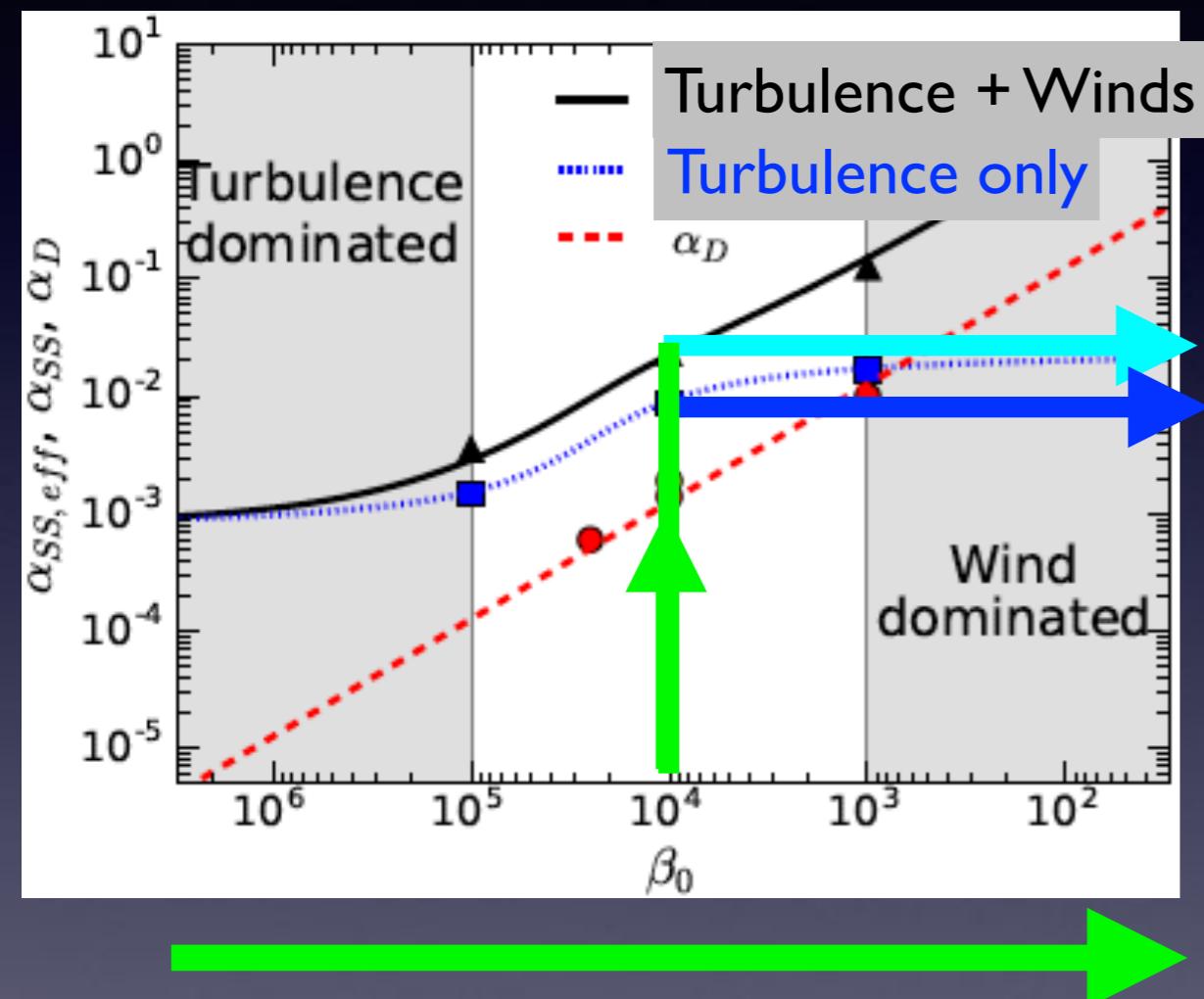
B-fields

I. Gas surface density

Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

$$\Sigma_g = \frac{\dot{M}\Omega}{3\pi\alpha_{\text{GL}}c_s^2}$$



2. Dust height

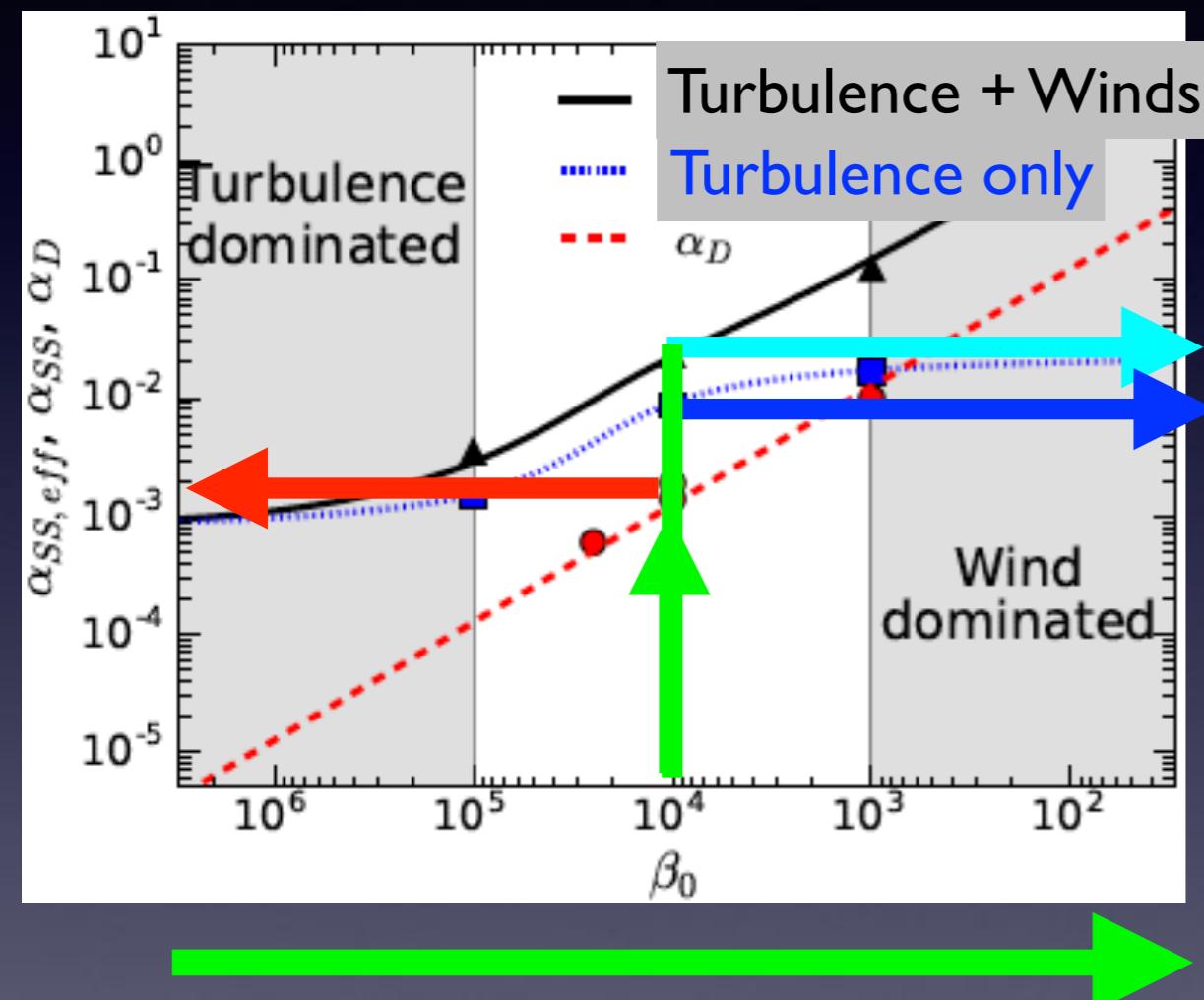
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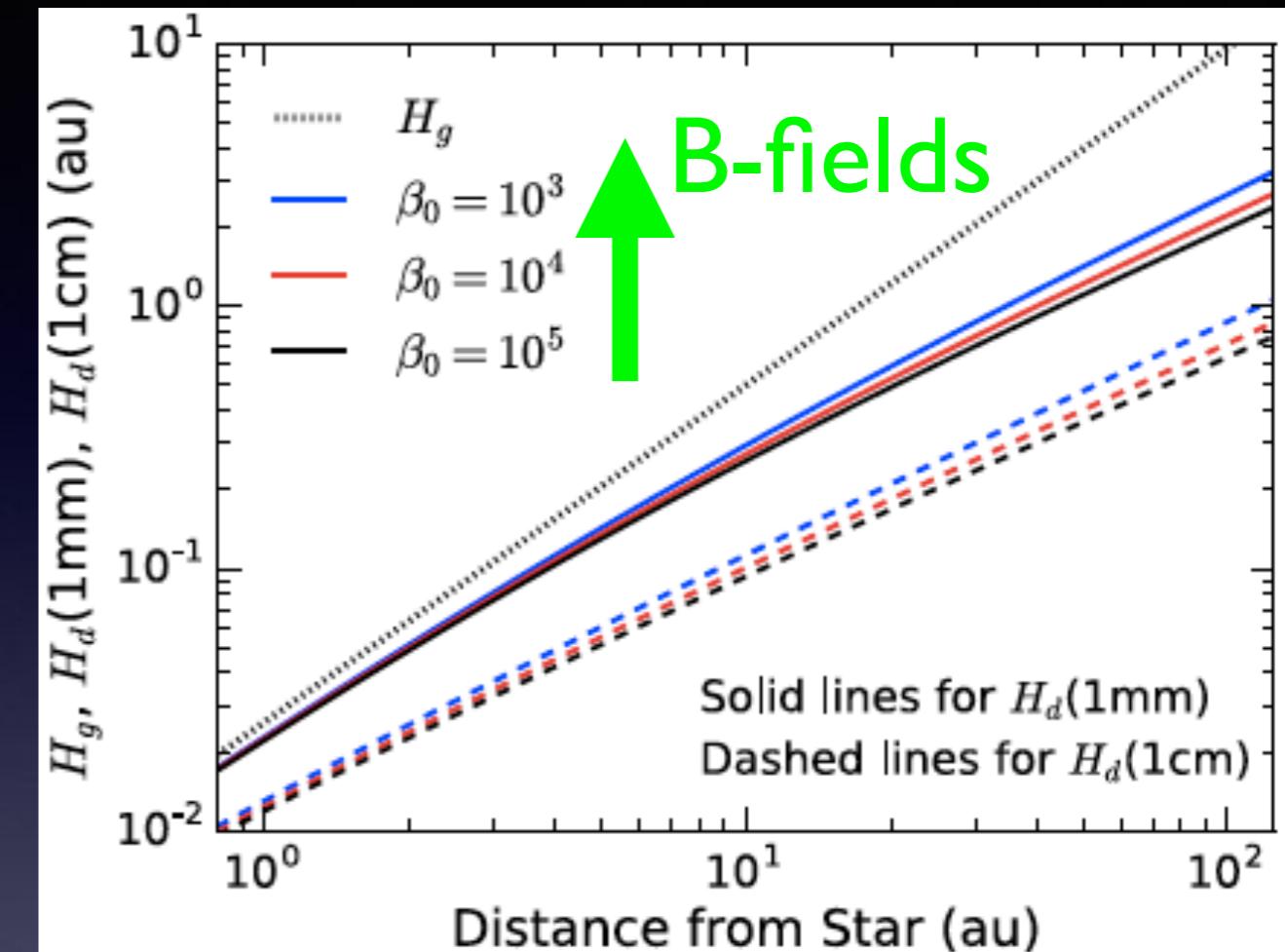
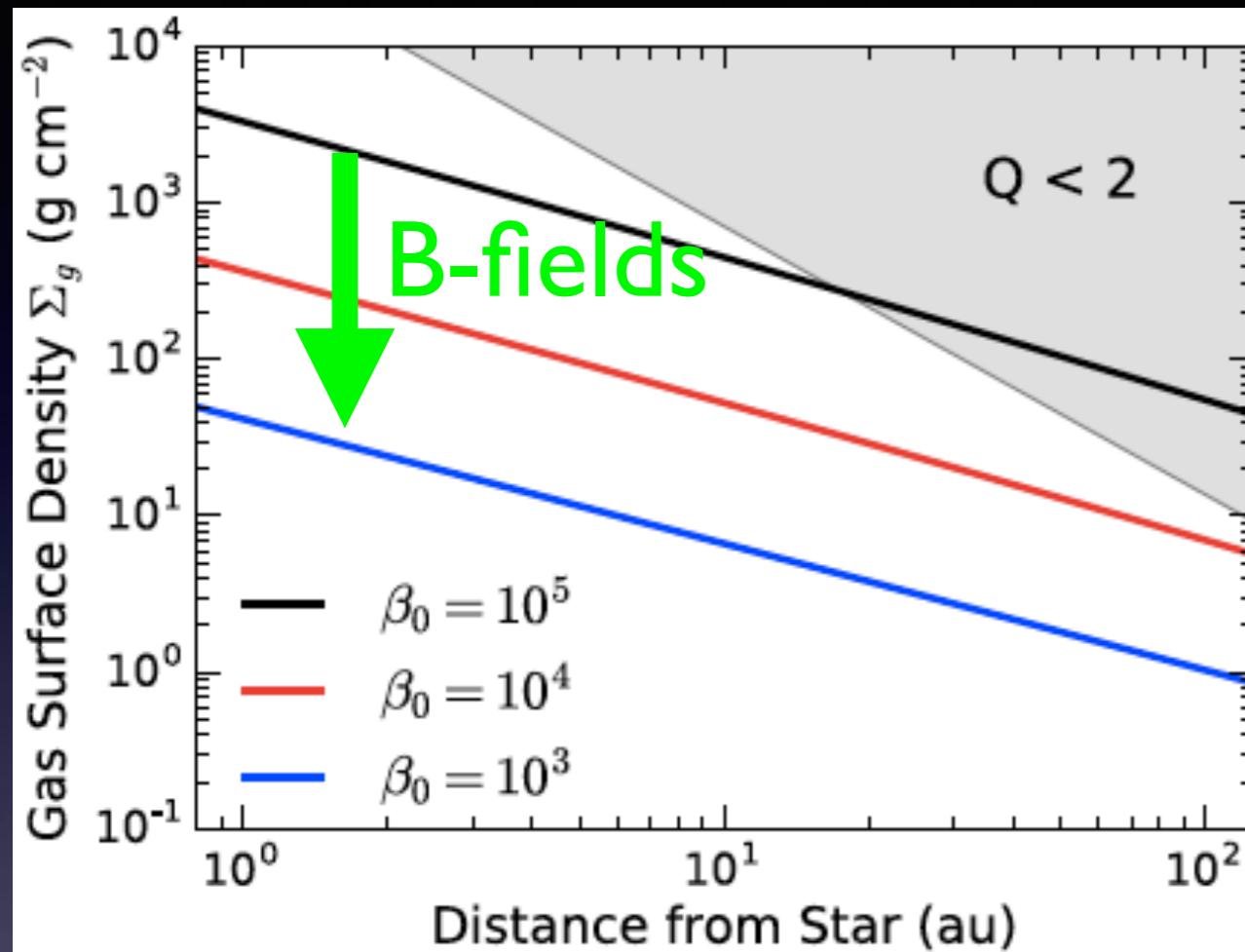
B-fields

2. Dust height

$$H_d = \left(1 + \frac{St}{\alpha_D} \right)^{-1/2} H_g$$

$$St \propto \frac{a}{\Sigma_g}$$

Resulting Disk Structures with Disk Winds



As B-fields are stronger,
surface density decreases
due to disk winds

Dust scale heights are
independent of B-fields

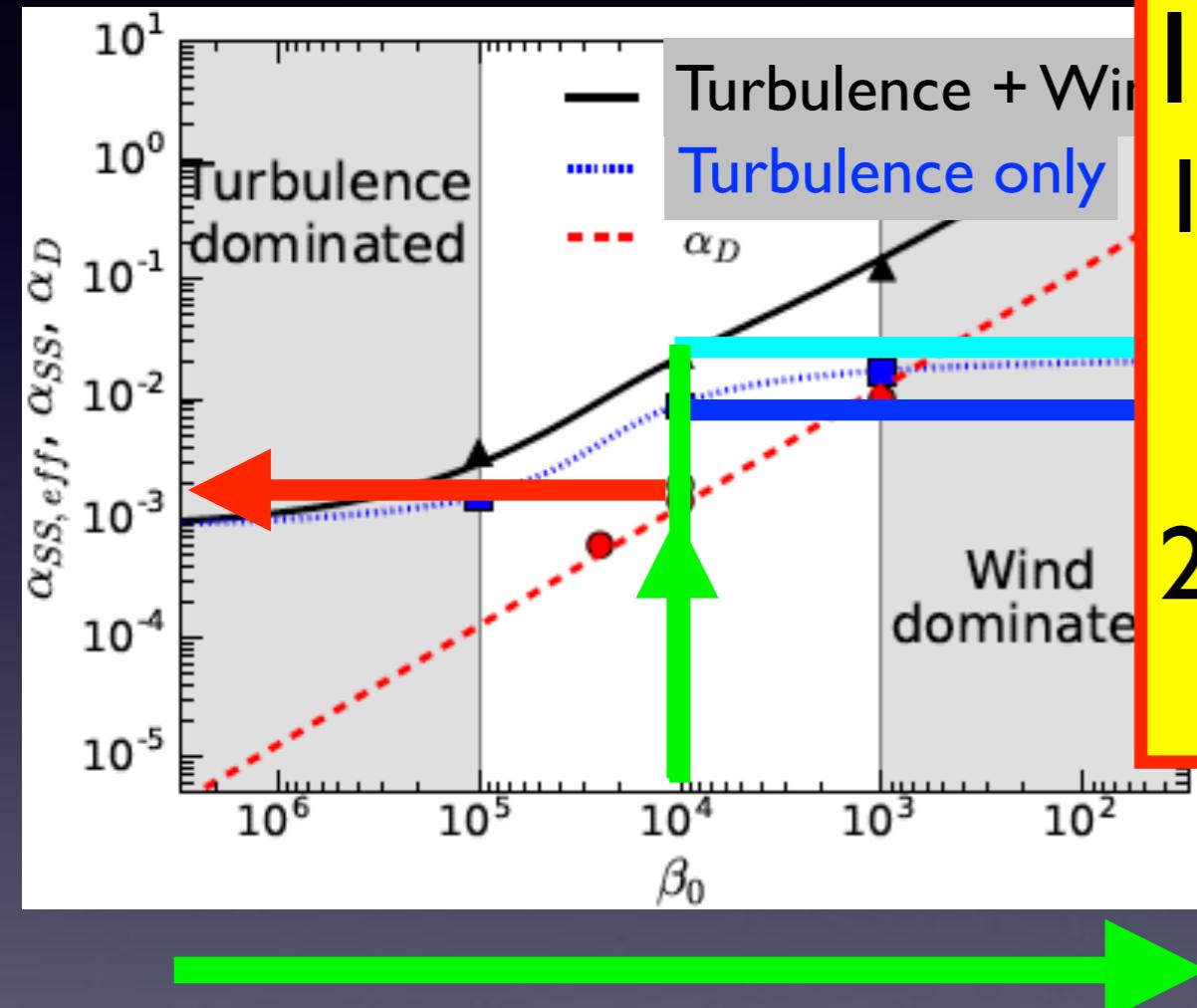
Results are obtained for given values of disk accretion rate, disk temperature

I. Gas surface density

Given that

$$\dot{M}, c_s^2 (\propto T_d), \Omega (\propto \sqrt{M_*})$$

$$\Sigma_g = \frac{\dot{M}\Omega}{3\pi\alpha_{\text{GL}}c_s^2}$$



B-fields

Inversely solve the problem

I. Find α_D (or β_0) with

$$H_d = 1 \text{ au} \text{ at } r = 100 \text{ au}$$

2. Find α_{GL} (or β_0) with

Σ_g that satisfies marginally GI

2. Dust height

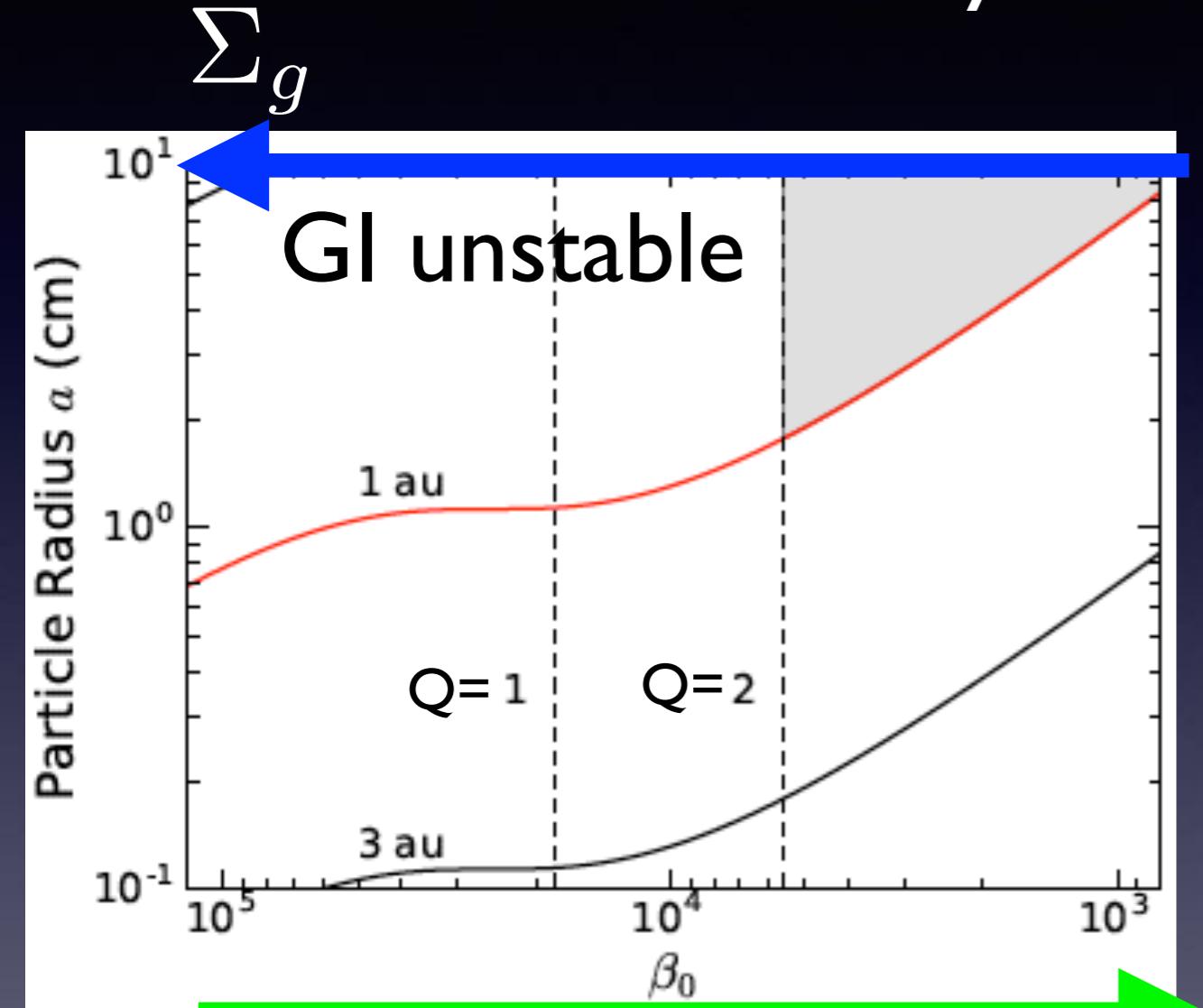
$$H_d = \left(1 + \frac{St}{\alpha_D} \right)^{-1/2} H_g$$

$$St \propto \frac{a}{\Sigma_g}$$

Minimum Size of Dust Particles at $r = 100$ au

Turbulence only

Turbulence + Winds

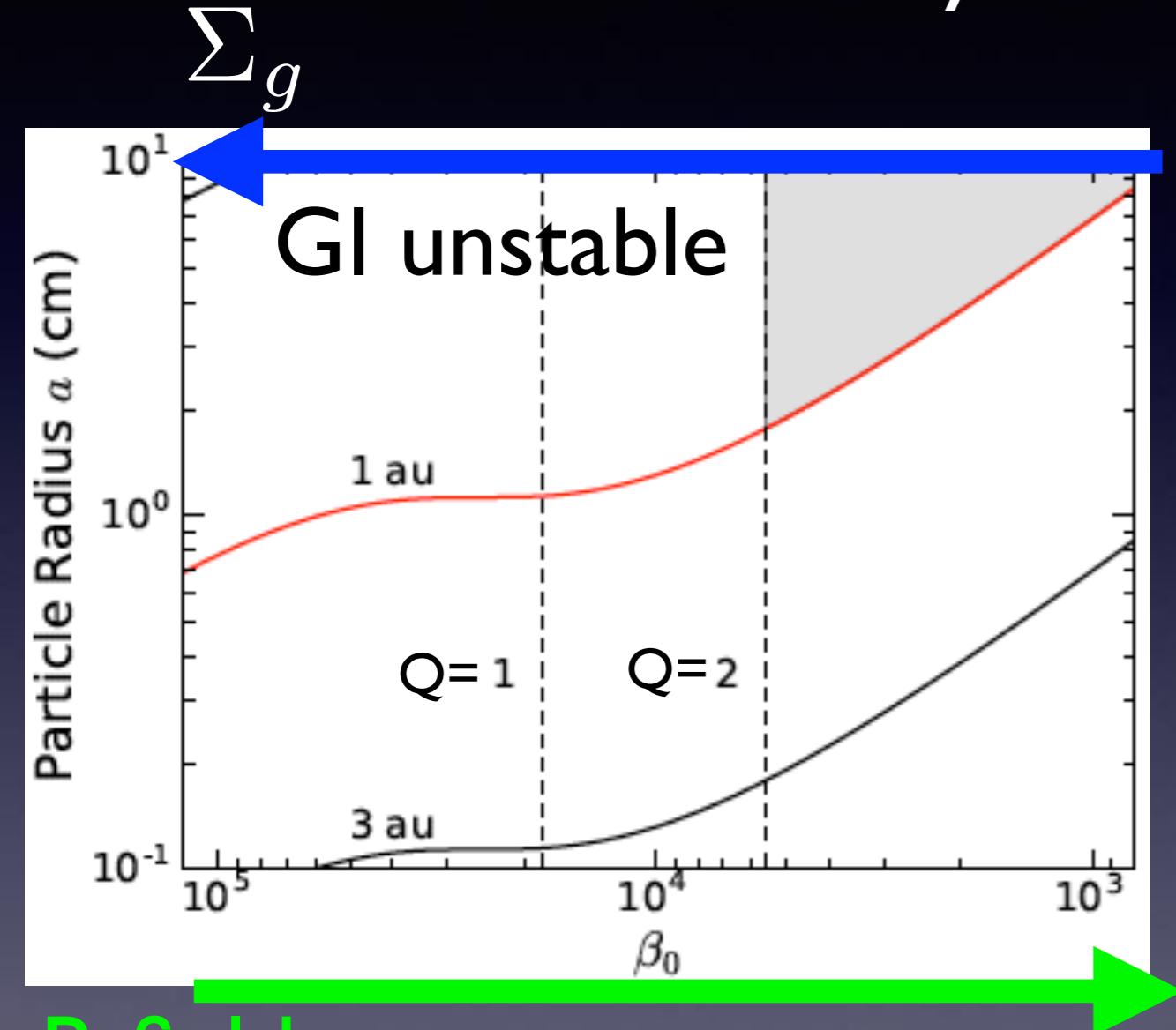


B-fields

Results are obtained for given values of disk accretion rate, disk temperature

Minimum Size of Dust Particles at $r = 100$ au

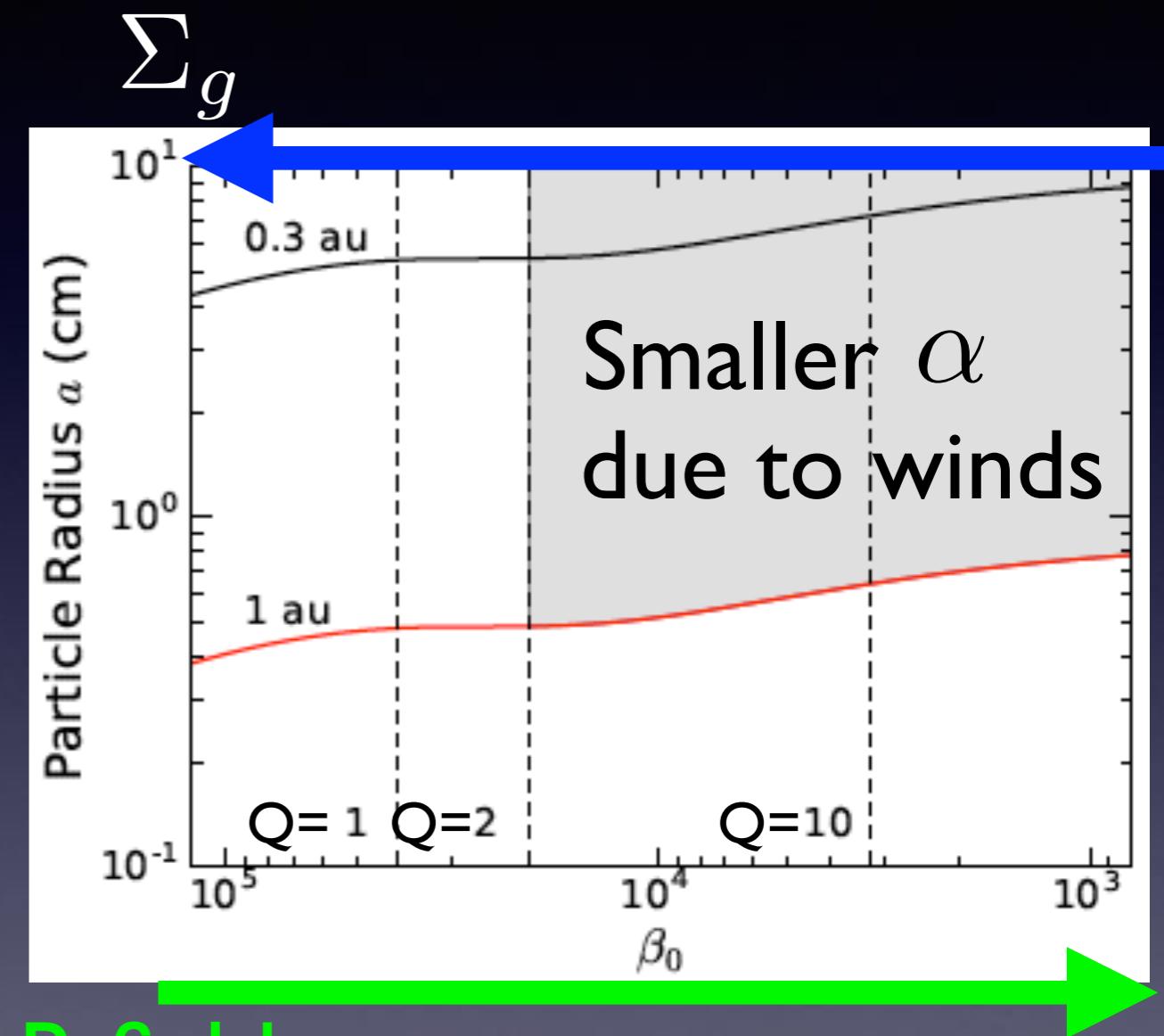
Turbulence only



B-fields

20 mm-sized dust is needed
to reproduce ALMA image

Turbulence + Winds

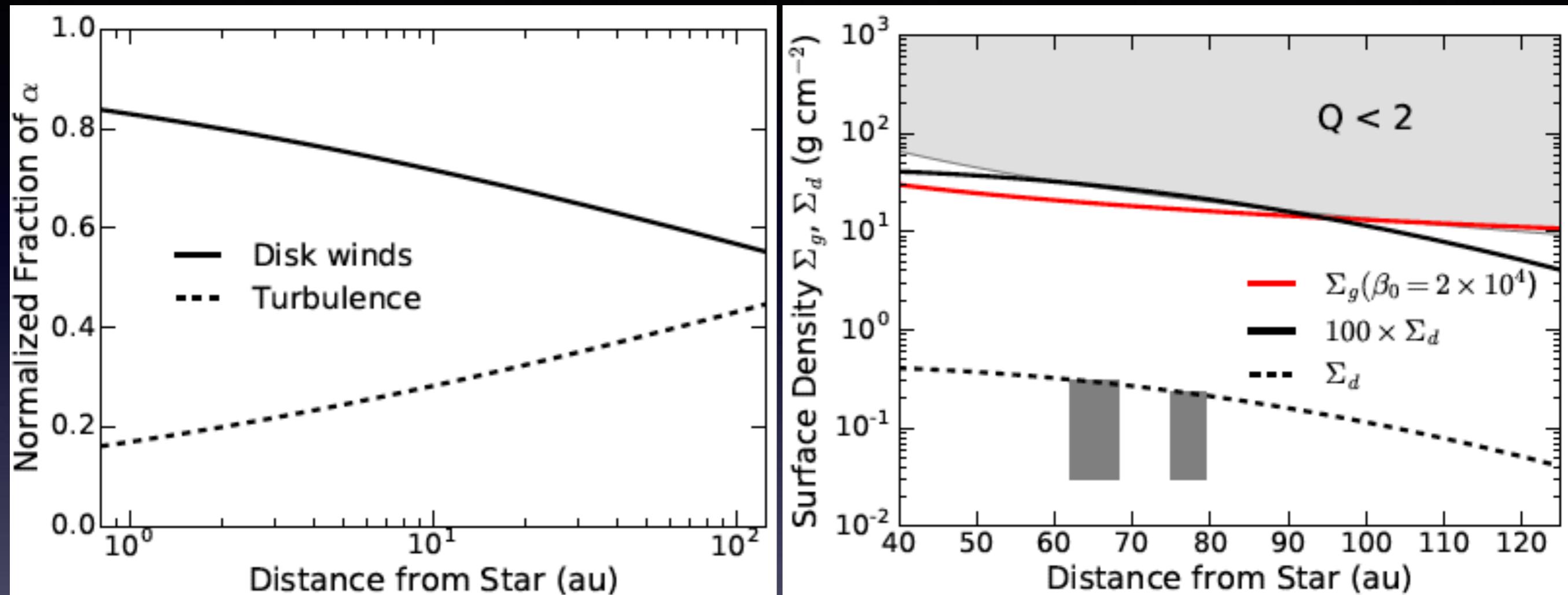


B-fields

4 mm-sized dust is needed
to reproduce ALMA image

Results are obtained for given values of disk accretion rate, disk temperature

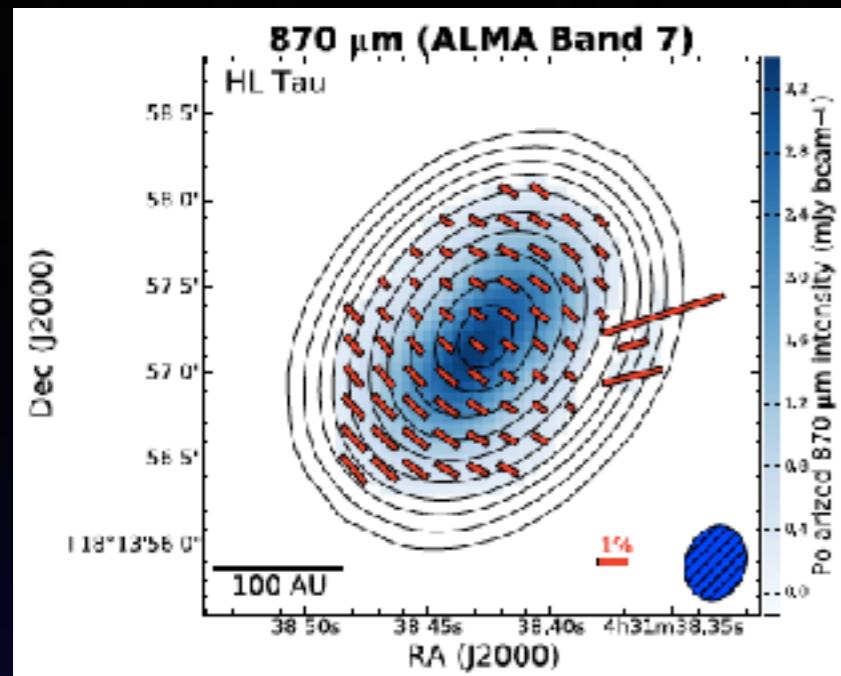
Resulting Global Structure of the HL Tau Disk



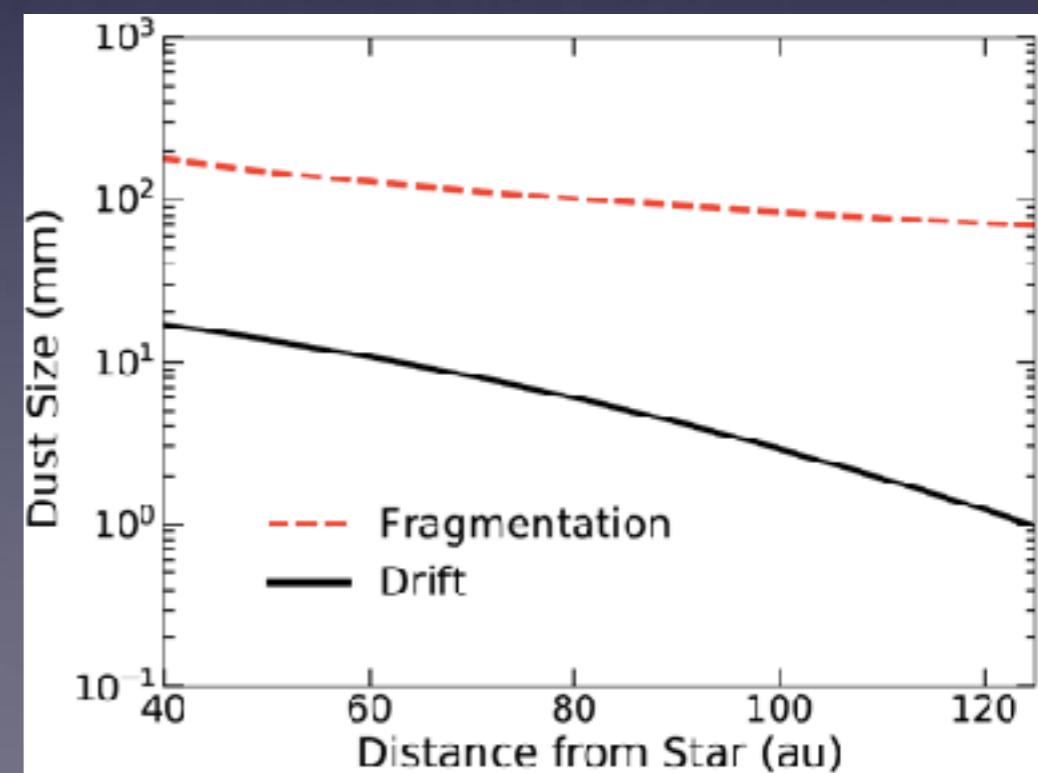
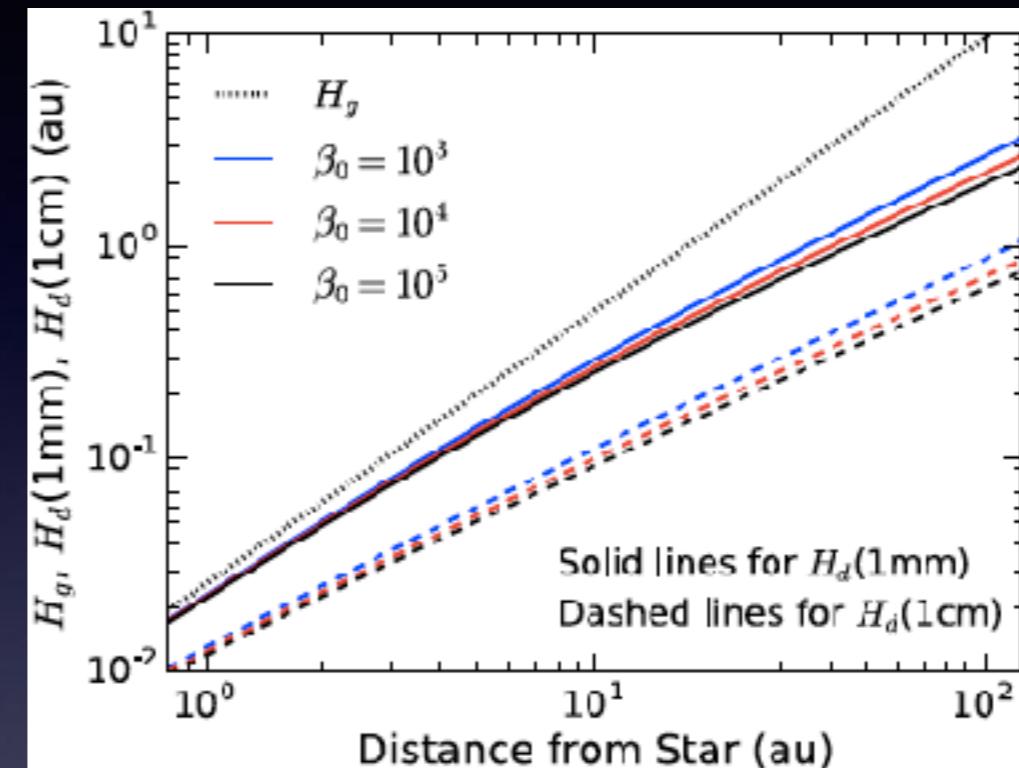
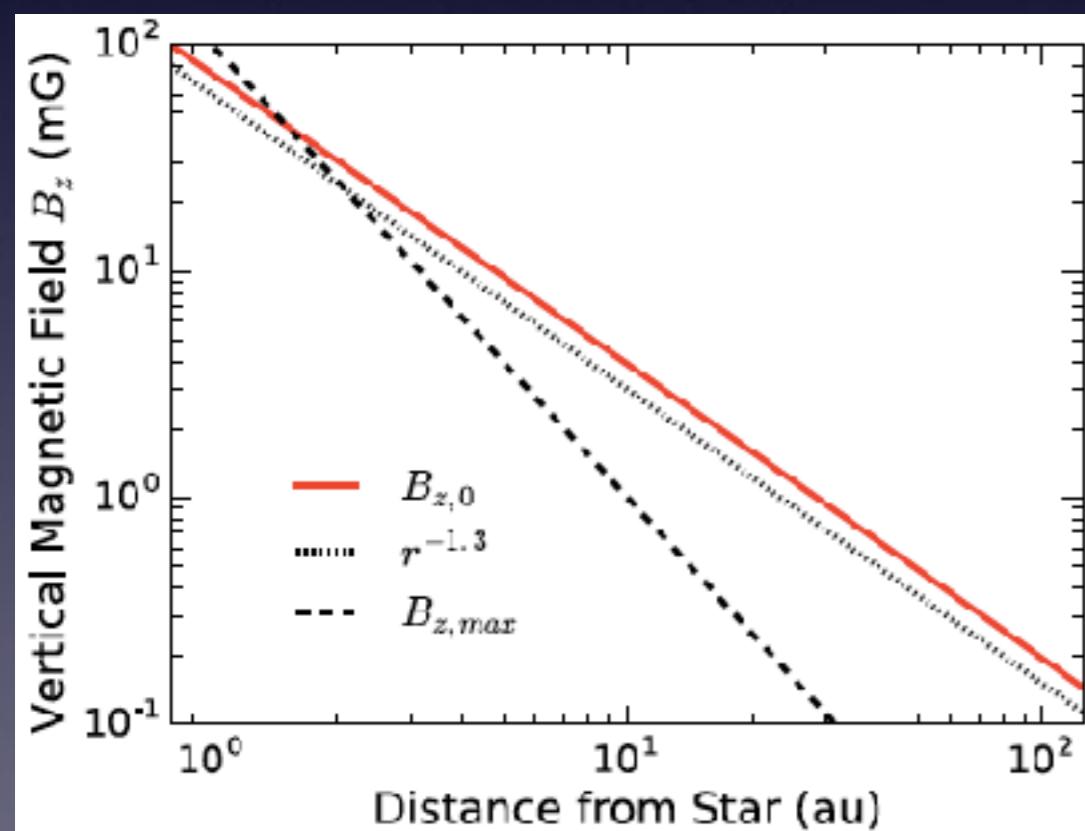
Disk winds transport the most of angular momentum (50-80 %) across the entire region of the disk

The gas-to-dust rate varies along the distance from the star (lower in the inner region & higher in the outer region)

Next Step I: Application to Polarization (Preliminary)



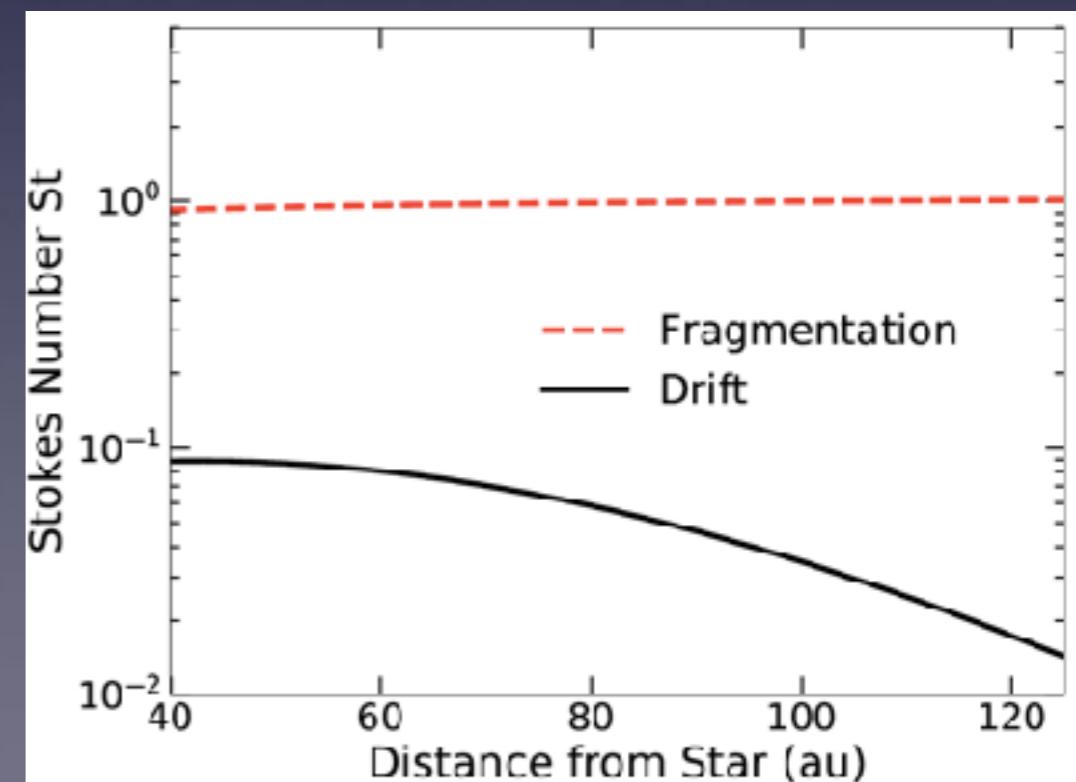
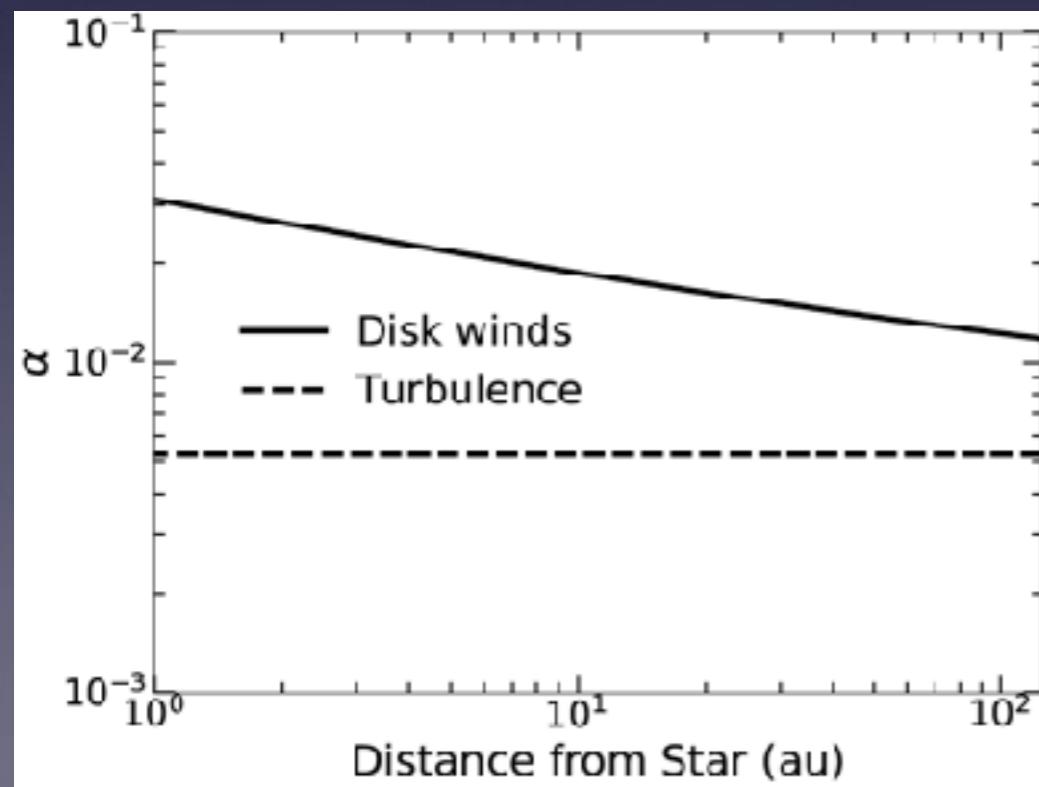
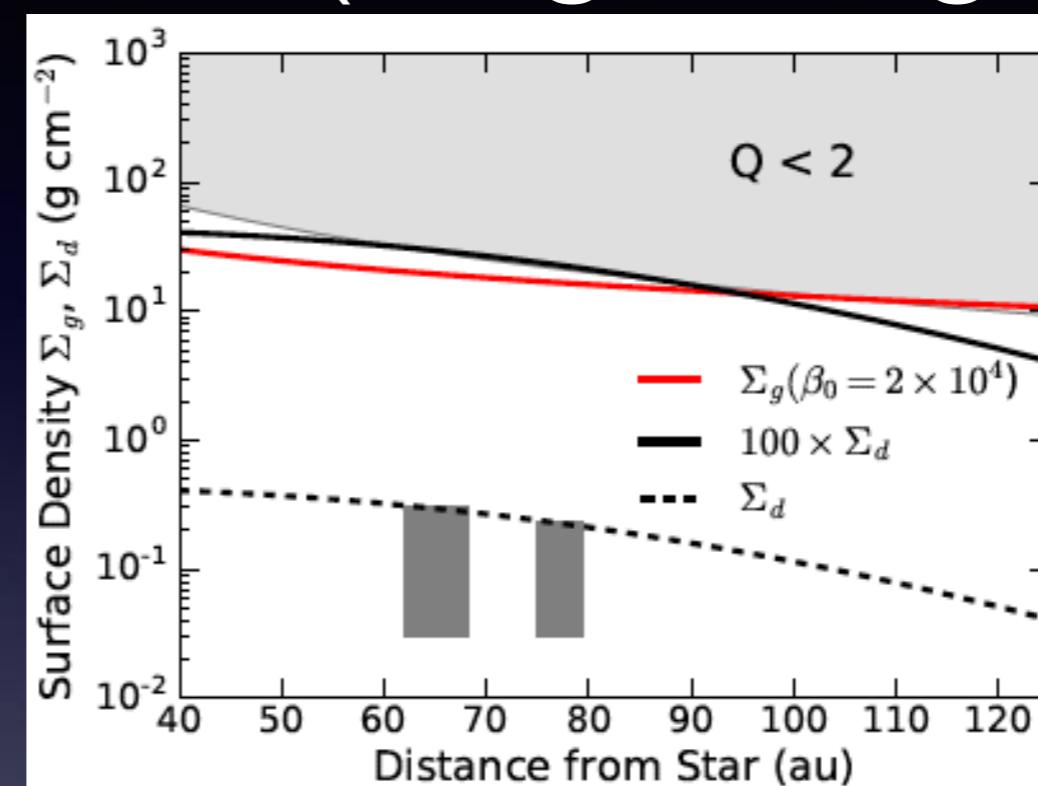
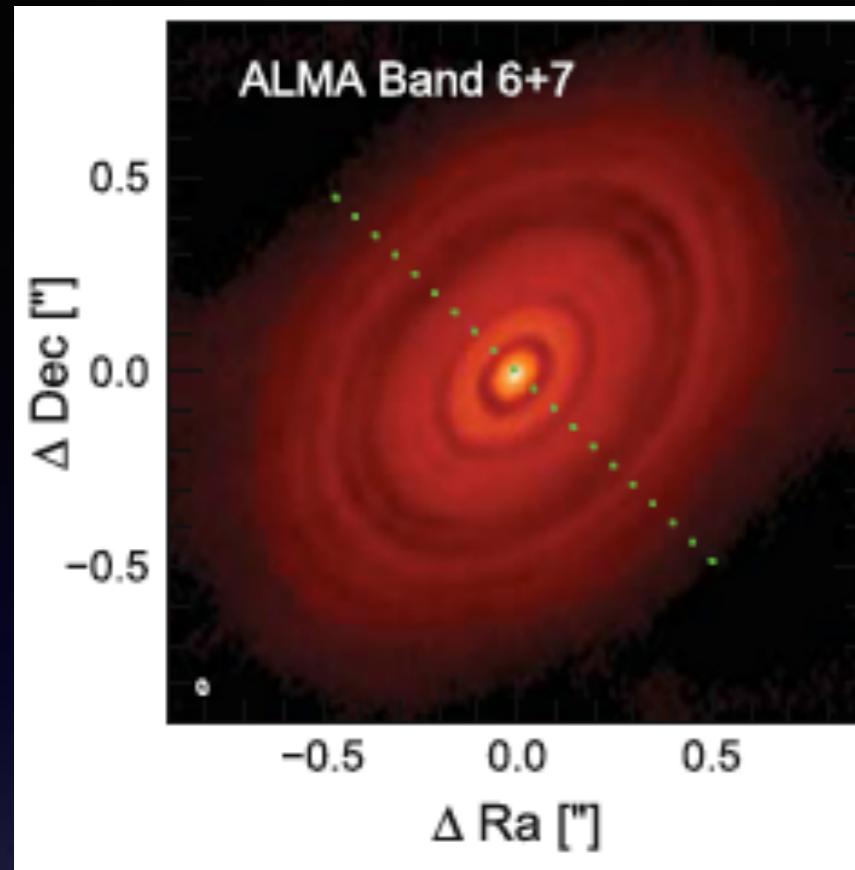
Kataoka et al 2017, Stephens et al 2017



JVLA data will be combined, too

Carrasco-Gonzalez et al 2016

Next Step 2: Application to Thermal emission (Origins of gaps)



Summary

Hasegawa et al 2017,ApJ, 845, 31

- ALMA observations of the HL Tau disk can advance our understanding of **disk evolution**
- Subsequent radiative transfer modeling suggests a higher degree of dust settling for the actively accreting disk
- Developed the simple, semi-analytical model, taking into account magnetically induced disk winds
- Our results indicate the importance of **magnetically induced disk winds** to fully reproduce the global configuration
- Followup work will be performed to obtain a better understanding of **polarization observations** and to fully